CHEMICAL ENGINEERING RESEARCH AND DESIGN 92 (2014) 672–678

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

# Conical spouted bed combustor for clean valorization of sludge wastes from paper industry to generate energy

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## ABSTRACT

Clean technology of spouted bed is applied to paper industry wastes for energy valorization of de-inking sludge by combustion in a temperature range from 500 to 700 °C. The stable operating conditions for beds of different types of inert material (silica sand) have been tested in spouting regime over a wide range of operating conditions. The radial and axial temperature profiles of sand beds have been measured to improve the combustion efficiency of wastes. Thereafter, that sand providing the higher bed temperature has been applied as the fluidization material for combustion of papermaking sludge using a mass ratio of 2:1 (dry basis). The optimal conditions for the inlet air flow rate and temperature have been determined experimentally by maximizing the combustion efficiency and minimizing the amount of volatile compounds in the flue gas.

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*Keywords:* Combustion efficiency; Clean valorization; Conical spouted bed combustor; Energy valorization; Thermal operating conditions; Sludge wastes

## 1. Introduction

Pollution prevention in the papermaking industry is a major worldwide concern (European Commission, 2013). In this sense, sludge is the largest by-product and its disposal is a major environmental problem (Bajpai, 2012). Because of the wide variety of processes, raw materials, and finished products involved, the complexity of the sludges generated in papermaking industry becomes rather high, making them difficult to manage. Thus, over half of wastewater management costs are related to sludge handling (Mahmood and Elliott, 2006). In addition, the more extensive the recycling, the more deinking recycled paper used as feedstock and hence the greater the amount of sludge generated. The ultimate fate of the dewatered sludges from the pulp and paper industry is diverse. The management of these solid wastes relies on minimization (recycling, process improvement, feedstock quality), reuse (composting, land spreading, product valorization), energy recovery (thermal processing, anaerobic digestion), and landfill (Monte et al., 2009). In particular, thermal valorization has been commonly applied for large-scale disposal of these sludges (Caputo and Pelagagge, 2001; Xu and Lancaster, 2011), and especially in fluidized beds (Eldabbagh et al., 2005; Halonen et al., 1993; Latva-Somppi et al., 1998; Namkung et al., 2004; Shin et al., 2005). Also, co-firing of papermaking sludge and other fuels has been studied. For example, co-combustion with coal (Tsai et al., 2002), coal and wood bark (Van de Velden et al., 2007), and bark, solid recovered fuel (wood and plastics) and sewage sludge (Vainio et al., 2013) has been applied in fluidized beds. Other innovative techniques, such as fast pyrolysis by microwave radiation (Jiang and Ma, 2011), are in early stages of development.

In the same way, thermal processing in spouted bed devices has been applied for different solid fuels. Thus, the combustion of low-grade fuels in spouted beds has been explored long ago (Khoshnoodi and Weinberg, 1978).

Focusing on biomass-derived fuels in both spouted bed and spouted-fluidized bed systems, several works have been

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Received 26 July 2013; Received in revised form 17 December 2013; Accepted 4 January 2014
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http://dx.doi.org/10.1016/j.cherd.2014.01.008

**Nomenclature**

| | |
|---|---|
| $D_b$, $D_c$, $D_i$, $D_o$ | diameter of the top diameter of the stagnant bed, of the column, of the dryer bottom, and of the bed inlet, respectively, m |
| $d_p$ | particle diameter, m |
| $\bar{d}_S$ | mean Sauter diameter, m |
| $H_c$, $H_{cone}$, $H_o$ | height of the cylindrical section of the combustor, of the conical section and of the stagnant bed, respectively, m |
| $Q_{air}$ | flow of air, $m^3\,s^{-1}$ |
| R | radius of conical combustor at each bed level, m |
| T | temperature, °C |
| $u$, $u_o$ | gas velocity referred to $D_i$ and to $D_o$, respectively, $m\,s^{-1}$ |
| X | moisture content (dry basis), wt% |
| $x_{steel}$, $x_{ins}$ | thickness of the reactor wall and of the insulating, respectively, m |
| z, r | axial and radial positions, respectively, m |
| *Greek letters* | |
| $\varepsilon_o$ | voidage of static bed |
| $\phi$ | shape factor |
| $\gamma$ | angle of the conical combustor,° |
| $\rho_s$ | density of solid, kg/m$^3$ |

reported in the literature. For instance, combustion of wood charcoal (Rasul, 2001), sewage sludge (Barz, 2003), rice husks (Albina, 2006; Fang et al., 2004; Pimchuai et al., 2010), cork (San José et al., 2006) or vineyard pruning wastes (San José et al., 2013a). More recently, other opportunities such as gasification of mangrove wood charcoal (Abdul Salam and Bhattacharya, 2006), co-gasification of microalgae and coal (Alghurabie et al., 2013) and microalgae (Harman-Ware et al., 2013) have been studied.

Although very recently the feasibility of a conical spouted bed system has been proven for drying papermaking sludge (San José et al., 2013b), to our knowledge the present study is the first dealing with incineration of paper sludge wastes in a spouted bed combustor.

In this paper, clean technology of spouted bed is applied to energy obtaining from paper industry wastes. With this aim, stable operating conditions have been determined in a wide range of operating conditions. In order to improve combustion efficiency, beds consisting of sludge wastes have been dried as first step of combustion process. Axial and radial temperature profiles inside the combustor in beds of inert material (sand) have been measured. Concentration of combustion gases has been measured and combustion efficiency has been compared at different inlet gas temperatures.

## 2. Materials and methods

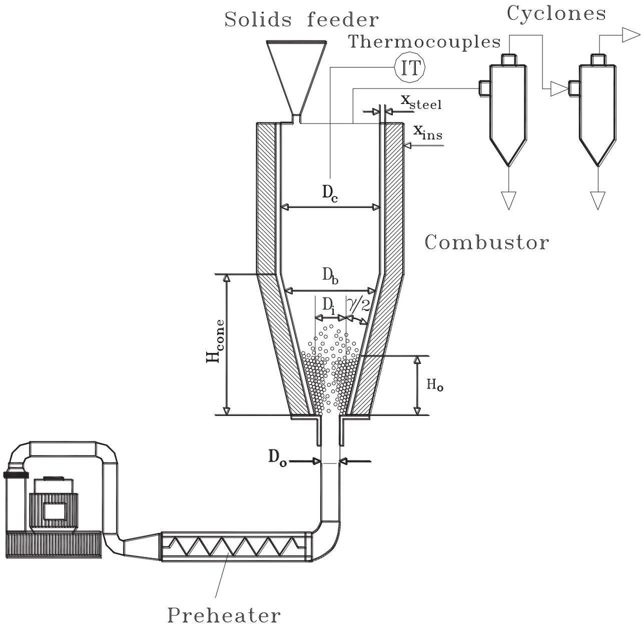

**Fig. 1 – Schematic diagram of the pilot plant and of the conical spouted bed combustor.**

The experimental study has been carried out in a pilot scale unit, Fig. 1, described in detail in a previous paper (San José et al., 2013a), basically consists of a conical spouted bed combustor made of AISI-310S heat-resistant stainless steel, two blowers, an electric resistance for heating the air, and two high efficiency cyclones to collect the ashes and fine particles. The combustor is provided with a solid feeder to supply the set sludge amount controlled by means of a frequency inverter to the annular zone of the bed.

Batch combustion of sludge wastes from paper industry has been carried out by preheating a bed of inert material (sand) inside the combustor in the temperature range 500–700 °C with air flow heated in an electric resistance, measured by two mass flowmeters controlled by computer with accuracy of ±0.5% (Olazar et al., 2004), between minimum spouting flow up to 20% over this value. When the set temperature of sand bed is achieved, the amount of sludge is fed into the combustor and the analysis of gases with the time starts.

The evolution of the drying of sludge wastes, as first step of combustion process, has been carried out from measurement of solid moisture content sampled, by means of a suction pump, with the time. Solid moisture results have been checked with those obtained by the oven drying method at 105 °C up to constant weight.

The concentration of CO and $CO_2$ gases with the time in the flue gas has been analyzed by means of Testo 350 gas analyzer. This analyzer measures gases concentration and their temperature at the same time. The relative error for measurement of CO is ±2 ppm, for $CO_2$ ±0.3 vol% and for temperature ±0.4 °C in −100 to 200 °C and ±1 °C at other ranges. Combustion process has been run three times at each bed temperature and the mean values have been calculated.

In order to quantify energy thermal gradients gas temperature has been measured by means of 10 screened thermocouples K type (relative error the highest of ±0.75% or ±2.2° C) located at the inlet and outlet of the combustor as well as at several axial and radial positions inside the combustor, by a displacement device controlled by computer, Fig. 2, in the three zones of sludge beds in spouted bed regime during drying and combustion processes.

The inert material, Fig. 3, used as bed material in the study has been silica sand. Two fractions of silica sand have been separated by means of meshes in Filtra FTI-0300 sieving machine: fine fraction ($d_p$ <1 mm) and coarse fraction ($d_p$ ≥1 mm), whose properties are summarized in Table 1.

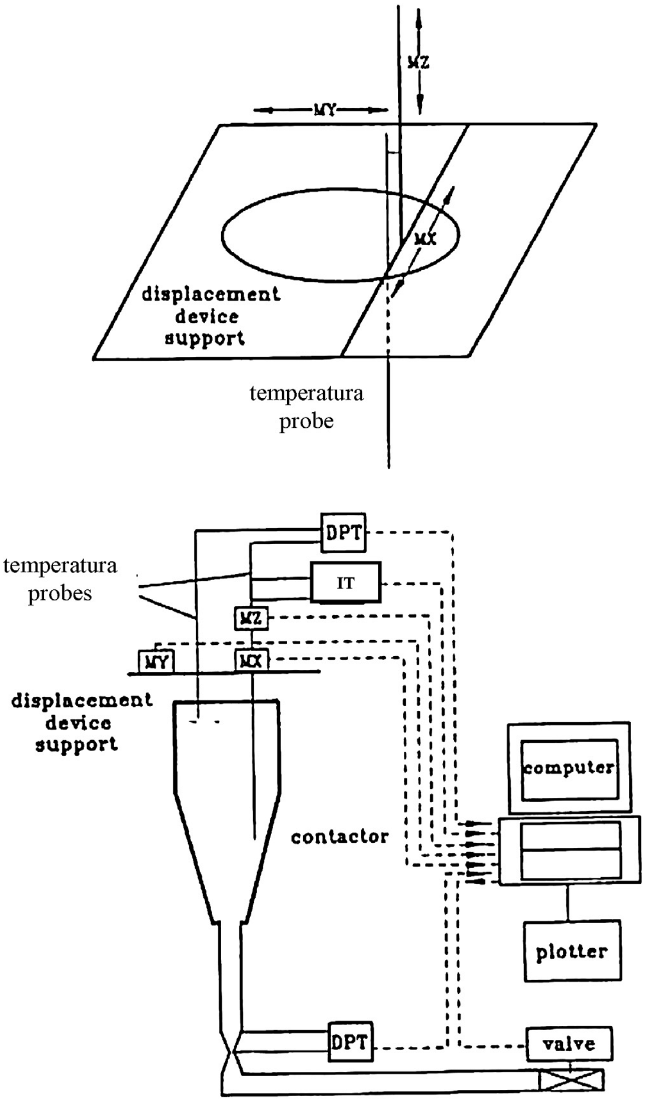

**Fig. 2 – Diagrammatic representation of the equipment and of the sampling device.**

Solid material used has been sludge wastes from paper deinking process of Sauter mean diameter 2.81 mm, density 1123 kg/m$^3$ and initial moisture content of 103 wt% in dry basis. Masses of beds consisting of binary mixtures of sand and sludge wastes are in the ratio 2:1 in the range 10–30 g.

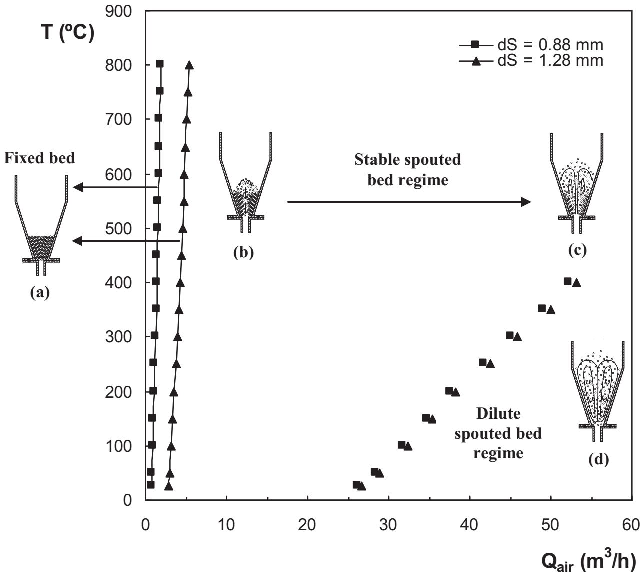

**Fig. 4 – Operation map for a bed of inert material (sand) of $\bar{d}_S$ of 0.88 and 1.28 with inlet gas temperature and outline of particle circulation at the different regimes in a conical spouted bed combustor. Experimental system: $\gamma = 36°$, $D_o = 0.03$ m.**

Solid moisture content has been measured by Mettler Toledo HR73 hygrometer (accuracy of ±0.01%). The low calorific value of dried sludge, measured with the bomb calorimeter type PARR 1341, is 4390 kJ/kg.

## 3. Results and discussion

Aiming in performing stable combustion process of sludge wastes, the stable operating conditions (minimum spouted bed and minimum dilute spouted bed velocities) of beds consisting of inert material (sand), sludge wastes and different binary mixtures have been determined from an experimental stability study in the pilot plant unit at inlet gas temperature from room temperature up to high temperature (700 °C).

Spouting regimes of beds consisting of an inert material (sand), as an example, in the conical spouted bed combustor for different velocities and inlet gas temperatures are shown in Fig. 4 in plots of inlet gas temperature, $T$, against air flow. In the map an outline of the situation of the particles in the

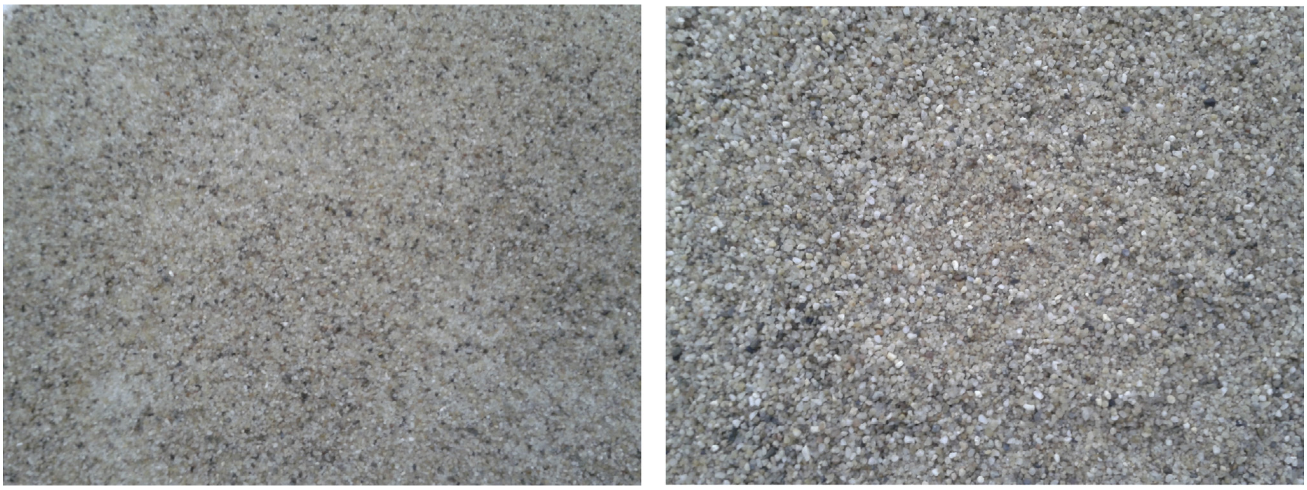

**Fig. 3 – Inert material (silica sand).**

**Table 1 – Physical properties of the inert material (silica sand particles).**

| Material | Particle diameter range (10−3) (m) | Sauter mean diameter $\bar{d}_S$ (10−3) (m) | Density $\rho$s (kg/m$^3$) | $T_{melting}$ (°C) | Thermal conductivity (W/cm °C) | Shape $\phi$ | Voidage $\varepsilon_0$ | Geldart classification |
|---|---|---|---|---|---|---|---|---|
| Silica sand (>98 wt% silica) | 0.8–1 | 0.88 | 2650 | 1713 | 0.0069 | 0.80 | 0.31 | A |
| | 1–1.8 | 1.28 | 2650 | | | 0.75 | 0.32 | B |

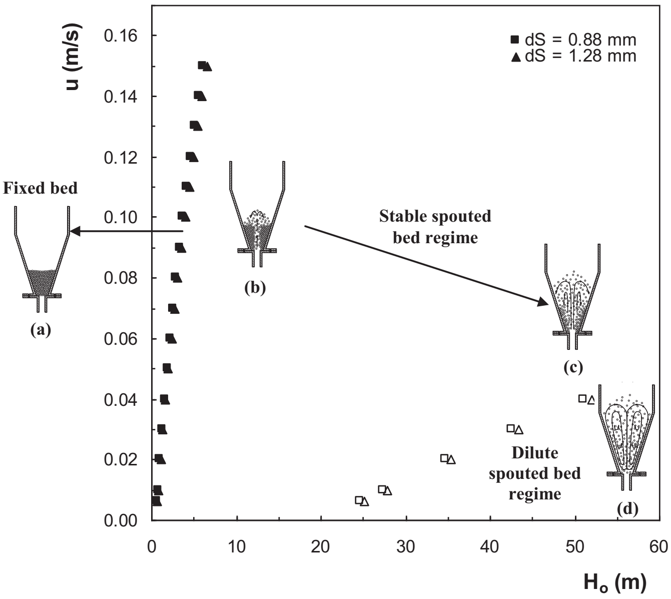

**Fig. 5 – Operation map for a bed of inert material (sand) of $\bar{d}_S$ of 0.88 and 1.28 with stagnant bed height and outline of particle circulation at the different regimes in a conical spouted bed combustor. Experimental system: $\gamma = 36°$, $D_o = 0.03$ m.**

combustor as gas flow is increased has been plotted in spouted bed regime for fixed bed (a), minimum spouting velocity (b), for the maximum value of this regime (transition) (c) and in the dilute (jet) spouted bed regime (d). The borders between the different contact regimes (plotted with experimental points) for each stagnant bed height have been obtained experimentally by increasing air flow; left points delimit the minimum spouting velocity for beds of sand and right points the beginning of dilute (jet) spouted bed regime.

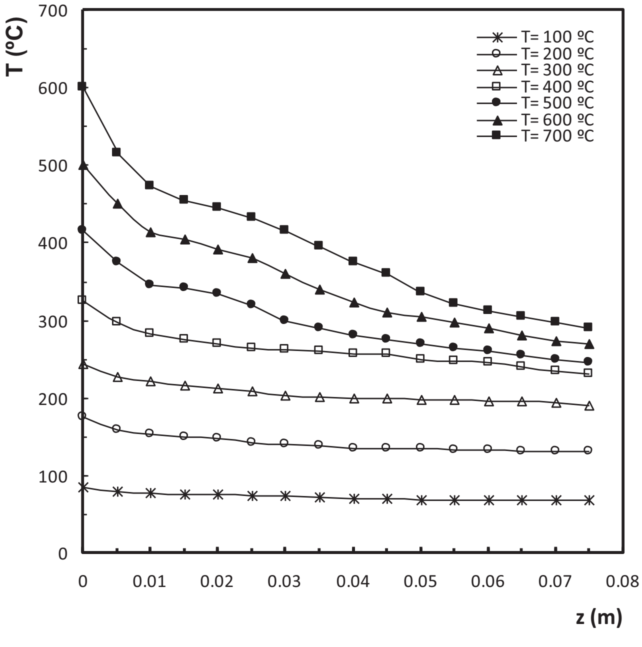

**Fig. 6 – Longitudinal temperature profiles at different levels of the combustor axis in beds of inert material (sand) at different inlet gas temperature $T = 100$, 200, 300, 400, 600 and 700 °C. Experimental system: $\gamma = 36°$, $D_o = 0.03$ m, bed of 808 g ($H_o = 0.08$ m) inert material (silica sand) of $\bar{d}_S = 1.28$ mm.**

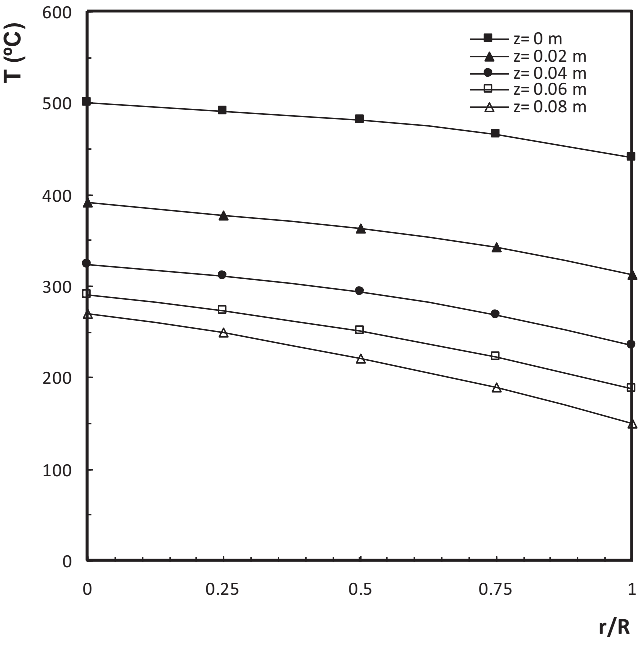

**Fig. 7 – Radial profiles of temperature at $T = 600\,^\circ C$. Experimental system: $\gamma = 36°$, $D_o = 0.03$ m, bed of 808 g ($H_o = 0.08$ m) inert material (silica sand) of $\bar{d}_S = 1.28$ mm.**

As it is observed, beds of inert material (sand) are stable at any studied temperature and the gas velocity necessary to reach the spouted bed regime increases as inlet gas temperature is increased, so the spouted bed zone decreases. Moreover, the greater the particle diameter, the higher the air flow corresponding to minimum spouting velocity and to minimum dilute spouted bed velocity.

Fig. 4 Minimum spouted and minimum dilute spouted bed (jet spouted) velocities for beds have been determined from pressure drop evolution. The air flow rate is increased from zero over the spouted bed regime, and then is decreased slowly until the fountain collapses at the minimum spouting velocity (Olazar et al., 1992), and then increasing the gas flow, minimum dilute (jet) spouted bed velocity is obtained and the corresponding pressure drop is the stable spouting pressure drop or operating pressure drop at the spouted bed regime. The procedure was repeated until a reproducible value was obtained.

In Fig. 5 the operating map, gas velocity, $u$, vs stagnant bed height, $H_o$, of beds of silica sand is plotted at 600 °C together with the particle situation in the contactor in the different regimes. As observed at low stagnant bed height dilute spouted bed regime is reached. Graphic of Fig. 5 shows that the increase in stagnant bed height gives way to an increase in minimum spouting velocity as well as in minimum dilute (jet) spouted bed velocity. Binary mixtures of sludge and inert material (sand) are stable in the 2:1 ratio and the operating conditions are between the range of stable operating conditions.

Good performance of the conical spouted bed contactor in combustion process of sludge wastes is influenced by bed temperature, where uniform temperature distribution in the whole bed is very important during the combustion. Temperature inside the conical combustor for beds consisting of different inert material (sand) has been measured in different longitudinal and radial positions at different operation conditions (flow and inlet gas temperature) and the corresponding axial and radial profiles have been plotted in Figs. 6 and 7, respectively.

In Fig. 6 temperature profiles at the axis of the conical spouted bed combustor in beds of stagnant bed height of 0.08 m of inert material (silica sand) of Sauter mean diameter of 1.28 mm at different inlet gas temperatures $T = 100$, 200, 300, 400, 500, 600 and 700 °C are plotted. As it is observed at high inlet gas temperature, over 400 °C, axial temperature profiles decrease from the base of the contactor towards the surface of the bed, and these profiles are more pronounced at the lowest region in the contactor. Whereas at inlet gas temperatures lower than 400 °C, axial temperature profiles in the bed are almost independent of bed height.

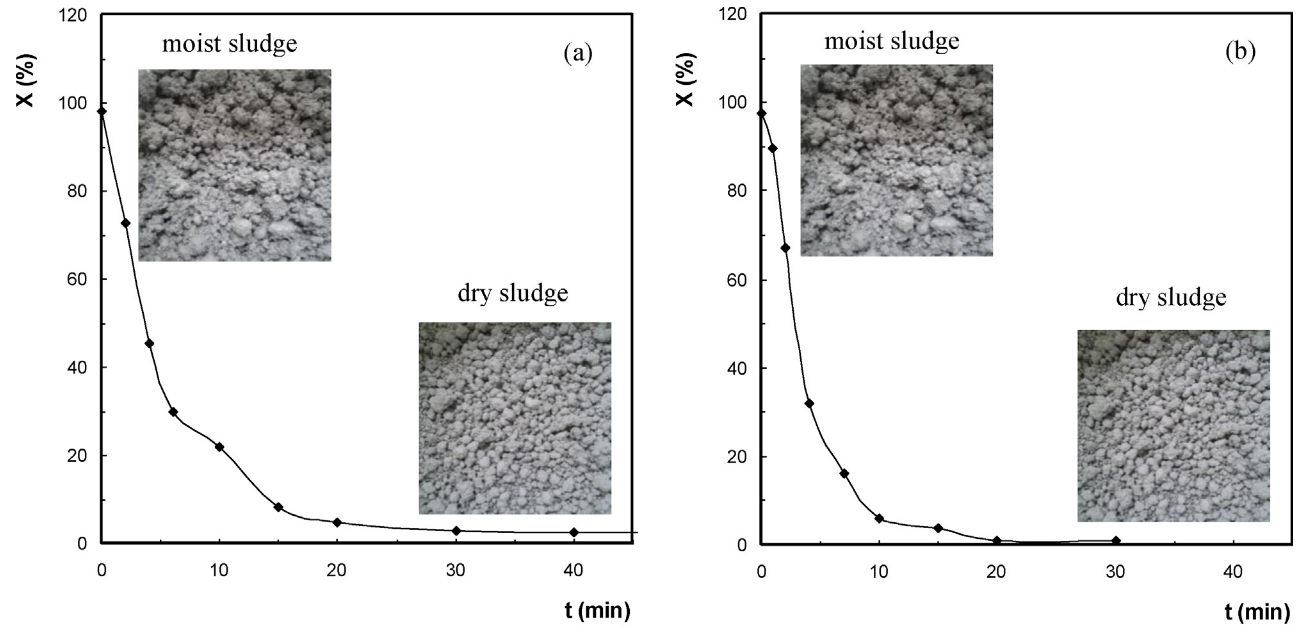

**Fig. 8 – Evolution of the moisture content of sludge with the time in drying of beds consisting of sludge wastes of $\bar{d}_S = 2.81$ and an initial moisture content of 100 wt% (dry basis) at drying gas temperature of 105 °C. Experimental system: $\gamma = 36°$; $D_o = 0.03$ m; $H_o = 0.14$ m, (a) at minimum spouting velocity, (b) at 30% above minimum spouting velocity.**

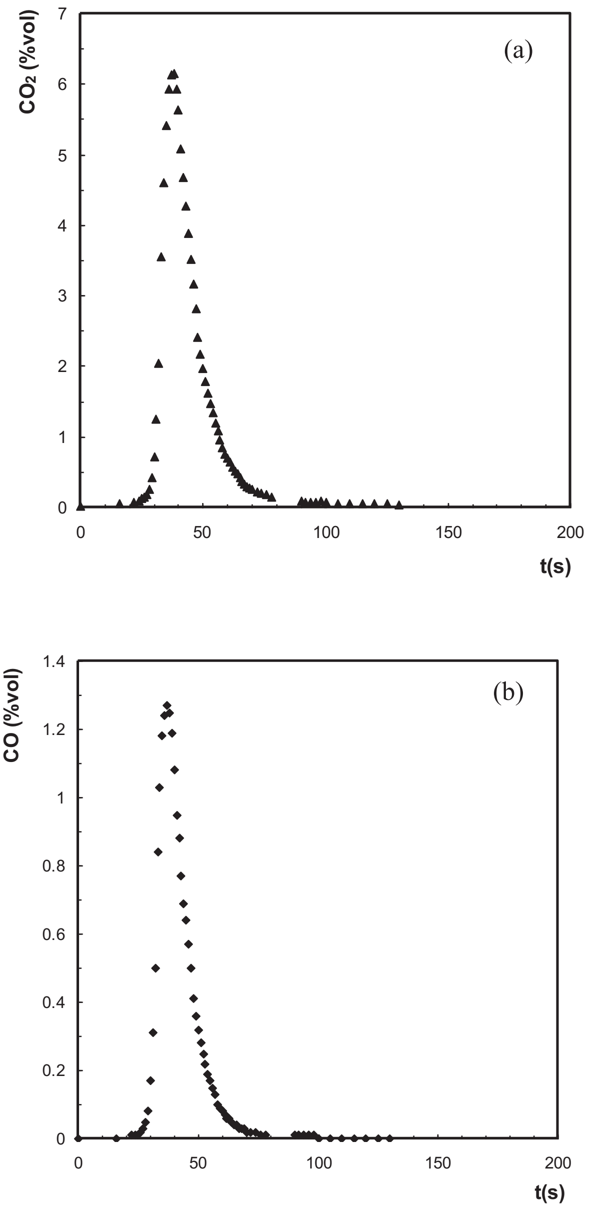

**Fig. 9 – Evolution of concentration of $CO_2$, CO (% volume) in the flue gases with the time during the batch combustion process of sludge wastes mixed with sand ($\bar{d}_S = 1.28$ mm, mass ratio of 1:2 in dry basis) at inlet gas temperature of 550 °C.**

Radial temperature profiles for beds of inert material (silica sand) of Sauter mean diameter of 1.28 mm of stagnant bed height of 0.08 m at inlet gas temperature of $T = 600$ °C are shown in Fig. 7 at different levels as an example. As it is observed bed temperature decreases slightly with radial position from the axis towards the combustor wall, and this effect is more noticeable at higher bed levels.

The evolution of the drying of sludge wastes, first step of the combustion, has been analyzed from measurement of solid moisture content sampled with the time. The experimental results of the evolution of the solid moisture content with the time at drying gas temperature of 105 °C for stagnant bed height, of $H_0 = 0.14$ cm corresponding to 400 g of moist sludge wastes together with photographs of the moist sludge at the beginning of the drying process and of dry sludge at the end of the process are shown in Fig. 8 at minimum spouted bed velocity (Fig. 8a) and at 30% above this velocity (Fig. 8b), for a system taken as an example.

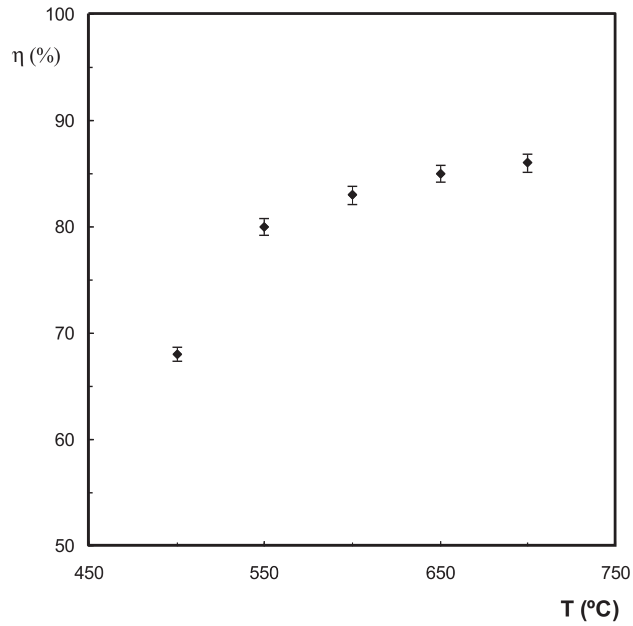

**Fig. 10 – Combustion efficiency in combustion of sludge wastes from paper deinking process with inlet gas temperature ranging from 450 to 700 °C in a conical spouted beds combustor.**

As it is observed, moisture content of sludge wastes decreases with the time from initial moisture content up to equilibrium moisture content and this decrease is more pronounced at short times. The moisture content evolution of sludge wastes displays a long constant-rate period followed by a falling-rate period. As drying velocity increases, time necessary to reach equilibrium moisture content decreases almost 40%. It is noticeable the different consistence of sludge depending on the moisture content, pasty consistence at high moisture content and stone consistence at equilibrium moisture content.

Efficiency of combustion process of sludge wastes has been calculated based on mean values of concentration of $CO_2$, CO (% volume) gases in the flue flow at each studied temperature by means of Eq. (1).

$$\eta = \frac{CO_2}{CO + CO_2} \tag{1}$$

The profiles of concentration of $CO_2$, CO (% volume) in the flue gases with the time during the batch combustion process of sludge wastes with inert material (sand) at a rate 2:1 at inlet gas temperature of 550 °C are shown in Fig. 9. As observed, concentration of $CO_2$, CO gases increases from zero, describes a sharp peak and decreases up to zero again. There is a short initial delay in the signals of gases concentration from the feeding of solid wastes to the beginning of the combustion process. Maximum values of concentration $CO_2$, CO gases are obtained at about 37 s and maximum concentration of $CO_2$ gas is more than five times higher than concentration of CO gas.

In Fig. 10, the experimental values of the combustion efficiency obtained in combustion process of sludge wastes with inert material (sand) in the (mass ratio of 1:2 in dry basis) are shown against inlet gas temperature from 500 to 700 °C. As it is observed at temperatures lower than 550 °C combustion efficiency is low, 68%. As inlet gas temperature is increased efficiency. Combustion efficiency increases asymptotically from 550 °C. The values of combustion efficiency are in the range 79–86% for inlet gas temperature between 550 and 700 °C. The high values of combustion efficiency for beds of sludge wastes confirm the good performance of the conical spouted bed combustor for clean valorization of sludge wastes to obtain energy.

## 4. Conclusions

The success of the clean technology of spouted bed applied to generate energy from papermaking sludge has been verified according to combustion efficiencies. To this aim, the operation maps for gas–solid flow regimes with inert material (sand as adjuvant particles) have been determined in a spouted bed contactor at 500–700 °C. The inert material (sand) tested showed a good spouting behaviour over a wide range of operating conditions, even though it was broader for the fine sand fraction ($d_p \leq 1$ mm). The minimum temperature for the combustion of papermaking sludge mixed with sand (mass ratio of 1:2 as dry basis) in spouting regime has been established at 550 °C. No unburned matter is observed above this temperature. However, with an inlet air flow rate corresponding to 30% above the minimum spouting velocity, the best operating temperature for this sludge was found to be 600 °C. The drying time for the sludge at 105 °C was estimated at 10 min. Under those conditions, the combustion of beds of sludge with the inert material (sand) yielded a combustion efficiency of 83%.

## Acknowledgment

This work was carried out with the financial support of the Spanish Ministry of Science and Innovation (Project TRA2009-0318 and Project CTQ2010-18697).

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